Chapter 01

Urban Greenery in Singapore

The Singapore Ministry of National Development Research Fund (MNDRF) for the built environment was awarded to Singapore's Building and Construction Authority (BCA) on 9 July 2009, to commission the National University of Singapore (NUS) as principal investigator and the National Parks Board (NParks) as lead organisation, to look closely at the green plot ratio (GnPR) in Singapore. Fieldwork support was sourced from the architectural consultant Broadway Malyan (Singapore) Ltd., the cost consultant Rider Levett Bucknall (Singapore) Ltd. and the structural consultant JS Tan & Associates (Singapore) Ltd., in the period from 11 July 2011 to 11 July 2012.

The GnPR was developed by Dr ONG Boon Lay to guide the provision of greenery in urban settings. GnPR is a step up from the gross plot ratio (GPR) currently deployed in Singapore to measure the development intensity of a building. The key difference between GnPR and current greenery metrics is that GnPR allows for a three-dimensional quantification of the greenery present on a site through the deployment of a common scientific measure known as the leaf area index (LAI). In comparison, current greenery metrics are largely two-dimensional. Given the improved precision in greenery quantification, GnPR seeks to be an enhanced greenery accounting tool. Several land use agencies are currently exploring the adoption of GnPR, including the Jurong Town Corporation (JTC), the Housing & Development Board (HDB) and BCA.

This book is undertaken in recognition of the presence of key knowledge gaps that prevent the widespread application of GnPR. These knowledge gaps were presented in the introduction as:

1. The need for the Optimal GnPR levels appropriate for the various land use types to be benchmarked against current levels of greenery provision.
2. That GnPR not only stipulates the greenery quantum but also encourages the concentration of some plants — especially existing native trees — the planting of certain local species, and the development of ecological or natural landscapes over manicured gardens.
3. That greenery provision comes with the inevitable installation capital and maintenance costs. There is therefore a need to understand the impact of the various GnPR provision levels (with such costs taken into consideration) prior to determining the GnPR implementation guidelines.

This book is multi-faceted in nature, comprising several stages. It has two specific objectives:

- To identify the impact of various greenery provision levels on their installation capital and maintenance costs;
- To give potential recommendations and guidelines for the implementation of optimal GnPR levels, within an urban design framework to facilitate a sustainable landscape for Singapore.

The book's survey fieldwork commenced in March 2010, spanning over one year and nine months and mainly involved two key stages:

1. Consultancy stage: where a building audit was used to determine the GnPR of 100 existing buildings in Singapore, based on current greenery provisions and desktop simulation studies to increase

GnPR, within an urban design framework, and with respect to installation cost, maintenance costs and structural limitations.

2. Statistical analysis report stage: where optimal GnPR levels for the major land use types were established on the basis of sound statistical analytical models.

No equivalent research similar to the multi-faceted complexity of this book's study has been undertaken elsewhere. The book details the rigorous setting up of the optimal GnPR levels and of more precisely regulating greenery provision within a direct real estate development in Singapore. The book could be a significant contributor to landscape architecture, urban design and the urban planning disciplines. With the first section introducing the book, providing the background, the objectives, the strategic value and collaboration benefits, the subsequent sections discuss the book's research stages, its methodology and key findings at each stage.

The second section discusses GnPR as an imperative metric for quantifying Singapore's greenery, offering GnPR calculation examples and their corresponding design applications. The third section describes the building audit of 100 existing buildings spread across the commercial, industrial and residential land use types. The fifth section discusses the statistical analysis using a robust heuristic GnPR optimisation model, to derive the optimal GnPR values for various land use types. Finally, the sixth section comprehensively discusses the various requirements relating to greenery provision in conjunction with the potential landscape guidelines, summarising the book's key findings and highlighting the book's contributions and recommendations.

GnPR an Indicator of Greenery in Singapore

The importance of nature conservation and greenery replacement emerged owing to land scarcity in Singapore. Singapore's greenery provision has thus been a key priority in the city's development and can be traced back to the period when the country was undergoing rapid industrialisation and urbanisation. The 1968 'Garden City' approach was a vision set by the government to integrate the environment with direct real estate development that influenced subsequent environmental policies. Over the years, sustainability-oriented concepts and strategies have been introduced under the Singapore Green Plan (introduced in 1992, reviewed in 1999 and 2012, and now known as SGP2012) (MEWR, 2006; MEWR, 2019) and through initiative-based programmes like the 'Landscaping for Urban Spaces and High-Rises (LUSH)' programme (URA, 2009), the NParks Skyrise Greenery Award (NParks, 2008; NParks, 2019) and the Green Roof Incentive Scheme (GRIS) (NParks, 2019; NParks, 2011), which aim to encourage building owners to retrofit existing buildings with green features and to provide greenery spaces in new developments. Even though 95 per cent of Singapore's natural forests have been lost, careful and comprehensive planning has expanded the city state's green cover from 36 per cent to 47 per cent between 1986 and 2007, in the form of parks and green connectors (NParks, 2008).

Urban skyrise greenery, like gardens on roof tops or along building walls, is a potential way to increase greenery provision. Despite assumptions that roof top gardens are elaborate and require special roofs to bear their weight, most modern green roof technologies are lightweight and require minimum maintenance. A variety of local and overseas systems have been studied to measure the environmental benefits in dense urban areas, like the reduction of the urban heat island effect, increased biodiversity, thermal insulation and energy savings by reducing a building's cooling load, or the improvement of air quality by trapping airborne dust particles, and the reduction of rainwater flow via the absorption and evaporation of rain from soil and vegetation. Although skyrise greenery in high-density urban areas is viewed as one of the most rapidly developing building features, it has yet to be regulated and implemented on an extensive planning scale.

As mentioned earlier, a primary objective of this book is to derive appropriate skyrise greenery levels for different building types, using the GnPR concept and metric to help quantify this.

GnPR Definition and Calculation

GnPR was originally defined as the LAI of the greenery of a site — an ecological measure that assigns values to particular plants based on the surface area of greenery (Ong B. L., 2003). The current definition by NParks states that GnPR is 'the area weighted average leaf area index of a site' (Tan & Sia, 2009). GnPR can be expressed as shown in Eq. (1.1):

$$GnPR = \frac{total\ leaf\ area}{site\ area} = \frac{\sum LAI_1 \times Canopy\ Area_{1\ldots} + LAI_n \times Canopy\ Area_n}{Site\ Area}, \qquad (1.1)$$

where LAI is a leaf area index defined as the one-sided area of leaf tissue per unit ground surface area. LAI values for different plant types can be found in *Leaf Area Index of Tropical Plants: A Guidebook on Its Use in the Calculation of Green Plot Ratio* (Tan & Sia, 2009), published by NParks. In the guidebook, plants are categorised into groups — trees, palms, shrubs, ground covers and turf — with sub-groups defined by canopy density (for trees), canopy type (for palms) and structure (for shrubs). To calculate the GnPR of a direct real estate development, the plant types and canopy type should be identified, as well as the number of trees and the areas of turf and shrubs.

An example of the simple calculation of the GnPR in a building lot with a site area of 4,000 sq. m. and landscaped with two dense trees, three trees with open canopies, 11 solitary palms, 20 sq. m. of dicot shrubs and 1,500 sq. m. of turf, is illustrated in Fig. 1.1 while the GnPR stepwise calculation is presented in Table 1.1.

Fig. 1.1. An example of the GnPR calculation of a direct real estate development

Source: Author (2018; Broadway Malyan Ltd, 2012)

Table 1.1. The GnPR stepwise calculation (from left to right)

Plant	**Canopy type**	**Canopy area, sq. m. per unit (A)**	**LAI value (B)**	**Number of units (C)**	**Leaf area, A x B x C**
Trees	Dense	60	4	2	480
	Intermediate	60	3	0	0
	Open	60	2.5	3	450
Palm	Solitary	20	2.5	11	550
	Cluster	17	4	0	0
Shrub	Dicotyledonous	1	3.5	0	0
	Monocotyledonous	1	4.5	20	90
Turf			2	1500	0
Total leaf area					1,570.0
Site area					4,000.0
Green Plot Ratio	**Leaf area/Site area**				**0.4**

Source: Author, 2018; Broadway Malyan Ltd, 2012

Methodology

Over the years, sustainability-oriented concepts and policies like the LUSH programme, the International Skyrise Greenery Conference and the Skyrise Greenery awards, have been initiated by government agencies to encourage the greenery of built-up areas in Singapore. GnPR has been adopted by various government agencies and research groups as the greenery accounting tool linked to these greenery provision initiatives and their correlating environmental benefits. For example, the GnPR is deployed as the greenery provision measurement within a public or private non-residential development for the BCA Green Mark Building Award. Both HDB and JTC have also adopted GnPR as the accounting tool to quantify, plan and regulate the amount of greenery in housing and industrial estates. Several studies at NUS have adopted GnPR to study the relationship between the amount of greenery and the surface and ambient temperatures of a building, and between the amount of greenery and the overall high-density environment (Jones, 1992; Santamouris, 2001; Jusuf & Wong, 2009). However, the optimal GnPR level for the various land use types, as well as their installation and maintenance costs with respect to the various GnPR levels, have not been researched (Ong B., 1996; Ong B., 1999; Ong B. L., 2003; Ong, Ho, & Ho, 2012; Whitford, Ennos, & Handley, 2001; Yang & Ong, 2004). Therefore, this book seeks to ascertain the achievable GnPR values which can be incorporated for various building types via a series of design simulations and the statistical analysis of the resulting output data of the simulations.

Stage 1: The best landscaping technologies, practices and the kit of parts

Stage 1 comprises a comprehensive review of the existing greening and landscaping technologies and practices in Singapore and worldwide. The review establishes the broad planting strategies of greenery provision within a direct real estate development, as illustrated in Fig. 1.2 and outlined in Table 1.2.

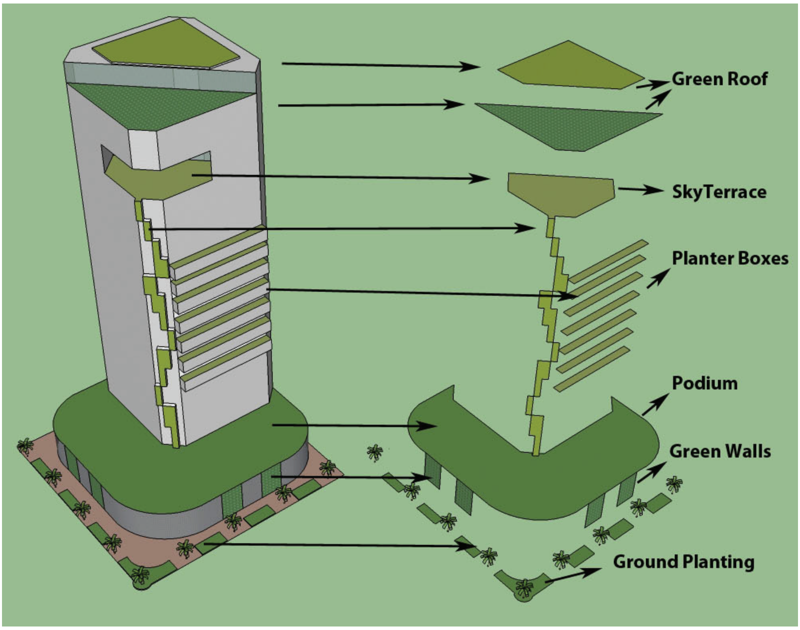

Fig. 1.2. An example of the GnPR calculation of a direct real estate development

Source: Author (2018; Broadway Malyan Ltd, 2012)

Table 1.2. Greenery provision planning strategies for a direct real estate development

1.	Landscaping on the ground level, including application of turf, trees, palms and shrubs.
2.	Landscaping on the podium and rooftop levels with the use of extensive and intensive green roof systems, trellises and planter boxes.
3.	Vertical greenery, such as green walls with support and module systems on the façade of a building or planter boxes on the balconies.
4.	Sky terraces and planting boxes or balconies integrated in a building structure.

Source: Author (2018)

These strategies are the landscape elements, as used and defined in the associated design simulations, denoted as the 'Kit of Parts'. They are applied at the design stage for what the study calls the 'existing scenario' as well as for four other simulated scenarios.

Stage 2: The building audit and building categorisation

The main objectives of the Building Audit stage were to measure the GnPR values for 100 existing buildings surveyed in Singapore, and to conduct the corresponding quantitative and qualitative analyses. The quantitative analysis included the different buildings' parameters — like each building's location, scale, height, mass, plot ratio, site coverage, gross floor ratio and existing GnPR. The qualitative analysis included a field survey conducted from March 2010 to July 2012, a period of about a year and nine months. The resulting 'Building Audit Report' mainly involved two key stages: the consultancy stage and the statistical analysis report stage (as mentioned at the beginning of this chapter).

The 100 buildings audited were categorised by land use (i.e. commercial, industrial, residential and residential-commercial mixed land use). Land use types were further sub-divided as follows:

- The commercial sector: i.e. office, hotel, retail, mixed-use typologies.
- The industrial sector: includes business or research park, factories and warehouse typologies.
- The residential sector: strata landed housing, public housing and condominium typologies.
- The mixed residential-commercial land use: includes both the private mixed and public mixed building types.

The building form was studied to explore the possibility of relating the landscaping strategies to specific building typologies. However, the 'Statistical Analysis Report' showed no such correlation between the GnPR and the building form. On the basis of the statistical analysis report, the following five building form categories that showed correlations with the GnPR levels are listed in Table 1.3.

Although strata-landed housing and social spaces were studied, their sample size was too small for significant recommendations to be made. Therefore, the results and the potential landscape guidelines for these building types are not included in this book.

Table 1.3. The five building form categories correlated with the GnPR levels

1.	Location (i.e. whether it is in the Central Area or outside the Central Area).
2.	Period of building construction (defined as before the year 2000 or after).
3.	Density (i.e. low, medium, medium-high, high or very high).
4.	Site coverage (i.e. low or high).
5.	Cost of greenery provision (in three subcategories: up to S$500,000; S$500,000–S$1 million; S$1 million–2.5 million; and more than S$2.5 million).

Source: Author (2018)

Further cost analysis using the design simulations model found the optimal GnPR value for business parks and landed housing building types to be lower than some of the range of values for the larger land use categories they fall under (i.e. industrial and residential land use types, respectively) owing to their respective lower GnPR values. This may have contributed to the overall lower GnPR value for their larger land use categories. After several evaluation rounds, categorisation by land use sub-type was determined as the most feasible means to calculate and apply the GnPR in Singapore. The existing GnPRs for seven out of the ten land use categories are summarised in Table 1.4.

Stage 3: The design response

To explore the extent of greenery achievable in the 100 buildings audited in the field survey, five GnPR design scenarios were devised to increase the buildings' GnPR values under a sequential (incremental) GnPR cost approach, in order to assess the correlation between the GnPR and cost (see Fig. 1.3):

1. **Existing scenario** considers the existing planting conditions of a building (i.e. all present greenery on the building's horizontal and vertical levels).
2. **Enhanced 1 scenario** is a simulated design scenario that maximises planting on the ground level.

Table 1.4. Existing GnPRs for the ten land use types: Means, medians and standard deviations

Sub-use	**Mean**
HDB flat	3.0923
Condominium	2.6767
Public-mix	0.2325
Private-mix	2.2425
Hotel	1.2233
Office	1.0656
Retail	0.9060
Mixed-commercial	0.8450
Bus Park	2.3440
Factory	0.5691
Total	**1.5930**

Source: Author (2018; Broadway Malyan Ltd, 2012)

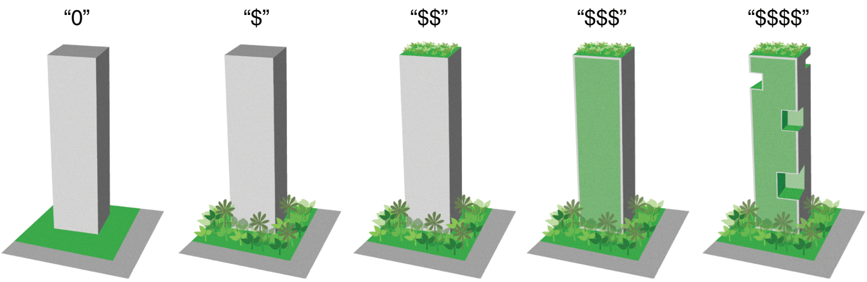

Fig. 1.3. Design scenarios: The sequential increase in greenery

Source: Author (2018; Broadway Malyan Ltd, 2012)

3. **Enhanced 2 scenario** adds on to the Enhanced 1 scenario and applies planting on rooftops and/or on podiums without any structural alterations.
4. **Maximum scenario** combines the Enhanced 1 and 2 scenarios with the addition of planting in the form of green walls on possible vertical surfaces without any major structural alterations to a building.

5. **Ultimate scenario** is the 'drawing board scenario' in which the building is assumed as yet-to-be-built, and structural changes are applied to the building design in order to maximise greenery; for example, through the addition of sky terraces.

Derivation of Existing Greenery Maintenance Cost

The 100 buildings audited were categorised into three land use types, namely, commercial land use (including mixed-use types), residential, and industrial. Residential land use was sub-divided into private and public residential land use sub-types. Key considerations included the pricing strategy among the contractors and the feedback from consultants. The site area analysis was based on the unit rates for existing maintenance costs and on a reasonable band to develop the building categorisation (see Table 1.5).

Table 1.5. Building categorisation by existing maintenance cost band

Land use		Site area (m^2)	Band
Commercial		2,000 to 9,999	Small
		10,000 to 19,999	Medium
		20,000 to 49,999	Large
		<2,000 and ≥50,000	Anomalies
Residential	Public	10,000 to 19,999	Small
		20,000 to 29,999	Medium
		30,000 to 49,999	Large
		<10,000 and ≥50,000	Anomalies
	Private	10,000 to 19,999	Small
		20,000 to 29,999	Medium
		30,000 to 49,999	Large
		<10,000 and ≥50,000	Anomalies
Industrial		7,000 to 17,999	Small
		18,000 to 26,999	Medium
		27,000 to 49,999	Large
		<7,000 and ≥50,000	Anomalies

NB. The building types are grouped by their corresponding land uses.
Source: Pomeroy & Broadway Malyan (2012); Author (2018)

Where available, the tender returns for the 100 buildings were consolidated. The returns were calculated by the cost per sq. m. to derive the average unit rate for each maintenance cost band. These average unit rates were applied to the buildings within their respective bands. An existing maintenance cost value, based on the individual site area, was imputed for each building.

Derivation of the Greenery Maintenance and Installation Capital Costs for the Enhanced 1, Enhanced 2, Maximum and Ultimate Design Scenarios

The GnPR design scenario maintenance costs — other than that of the 'Existing scenario' — were imputed and based on a ratio approach. The installation capital cost of greenery for all the 100 buildings in the 'Existing' scenario were imputed and compared with the greenery maintenance cost for all the 100 buildings, to derive a ratio of 0.1029. The implication was that for every S$1 of installation capital cost spent on greenery, S$0.1029 was spent on maintaining the greenery. This was applicable across all the components of the 'Kit of Parts' except for green walls, the methodology of which is explained in the next section.

Derivation of Maintenance Costs for Green Walls in the Maximum Design Scenario

Owing to the absence of available tender returns, the unit rate for the maintenance cost of green walls was determined based on an existing building with a green wall feature. The unit rate derived was applied to all buildings with the green wall option in the 'Maximum' design scenario.

The ten-year maintenance cost for the existing to ultimate design scenarios

The green wall maintenance cost was multiplied by ten to obtain the maintenance cost over a ten-year period. It should be noted that owing to the uncertainty of global economic and market conditions, inflation was not taken into account for this ten-year period.

Qualification of the maintenance and installation capital cost estimates

Only the maintenance cost for the buildings' 'Existing' scenarios was based on tender returns; this same basis was not applied to the other GnPR design scenarios. Besides the 'Existing' scenario, the maintenance and installation costs for the other GnPR design scenarios were derived using the ratio approach. The corresponding 13 cost estimates, owing to the unique nature of each building across each building category, are listed below but are not all inclusive:

1. Prevailing Goods and Services Tax
2. Professional consultancy fees
3. Authority submission fees
4. Costs fluctuations due to market conditions and overtime
5. Costs of tendering and contractual set-up
6. Contractual bonuses and penalties
7. Legal fees
8. Individual site constraints and latent conditions
9. Special equipment and tools
10. Negotiated contracts
11. Economies of scale achievable by various contractors due to their business operations
12. Irregular intervals or additional intervals of servicing
13. Current market competition

GnPR Statistical Analysis, Optimisation Objectives and Methodology

The purpose of the statistical analysis was to ascertain the optimal GnPR levels for selected land use categories via an in-depth investigation of several factors that influence the GnPR level of the direct real estate development, namely:

- Land use
- Year of building construction
- Building density
- Site coverage and location
- Installation, maintenance and total (i.e. installation + maintenance) costs.

The statistical analysis augmented the building audit of the 100 buildings. It examined the correlation between the GnPR and various key factors using the Analysis of Variance (ANOVA) model. The significant key factors that influenced GnPR levels were combined under an explanation-based and estimated General Linear Model (GLM).

The Marginal Cost Analysis (MCA) model was used to estimate the returns to scale that are expected of a profit-seeking private real estate developer-investor. It also allocates a building greenery budget that corresponds to the minima turning point at the margin per additional GnPR level, and beyond which there are no returns to scale. The MCA model, divided by land use type, was estimated and accordingly graphed together with its approximated polynomial function, to reflect the narrow GnPR band around its minimum U-shaped point. This narrow GnPR band is generally indicative of the optimal GnPR for each land use. The empirical data was obtained from the building audit of the 100 buildings.

A heuristic optimisation model was subsequently used to ascertain the optimal GnPR levels. The model adopts a heuristic algorithm that conforms to the usual practice of imposing constraints on a maximising objective function. An increasing GnPR function can be represented by incrementing the Standard Deviation (SD) from the mean GnPR, within the boundary range of between +0.25SD and +2.0SD. In practice and for normally distributed GnPR, approximately 95 per cent of the

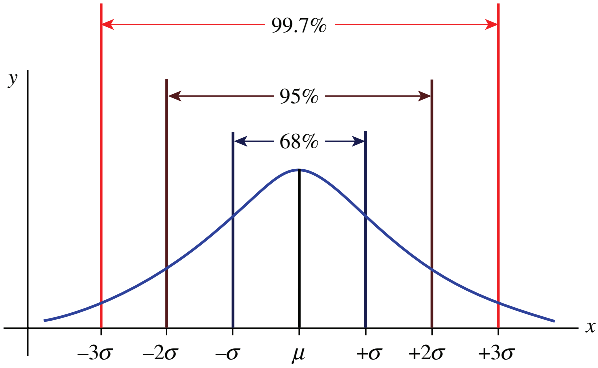

Fig. 1.4. The normal distribution of the GnPR

Source: Author (2018)

data points fall within the spread of ±1.96SD, i.e. ±2.0SD from its mean if the distribution of the GnPR values is normal, as illustrated in Fig. 1.4.

The 95 per cent confidence interval represents the extreme +2SD boundary condition for the GnPR, at which the optimal GnPR can be realistically achieved. The 3-step rule of the GnPR heuristic optimisation model is as follows:

1. The lowest and closest GnPR values for an incremental SD to the Ultimate GnPR was chosen as that particular highest boundary for the optimal GnPR level;
2. On practical grounds, the Optimum GnPR was appropriately presented as a range between the high and low optimal GnPRs;
3. The high optimal GnPR must not exceed the Ultimate GnPR value.

Analysis of the Factors Influencing GnPR

The importance of four main factors that influence GnPR levels — namely, the 'Period of building construction' (i.e. before or after 2000), 'Building site coverage' (i.e. below or more than 50 per cent), 'Building density' (i.e. the gross plot ratio) and 'Cost' — was derived from the foregoing statistical analysis. The following inferences can be made:

- The greenery innovation trend that is accepted by developers in Singapore tends to yield a higher GnPR for new developments than older developments.
- The lower the site coverage, the higher the GnPR as there is more greenery on the ground level and more available space for the application of the 'Kit of Parts'. From the building audit data, it was observed that greenery on the ground level is a significant contributor to a building's GnPR value for most building types except for office towers, as office buildings usually cover the maximum area of a building lot. Planting on the ground level is also a cheaper option as it does not require altering a building's existing structure.
- The statistical analysis showed that a GnPR of 2.0 is achievable, and with a budget of less than S$2 million.

Nevertheless, the coefficients of significance for 'building location' and 'building age' that were found in the statistical modelling cannot be readily applied to the estimation of the GnPR level for a specific land use owing to the small building sample within each category and the unequal distribution of samples in the various land use categories of this study. For example, all public mixed-use buildings in this study that were built before the year of 2000 had relatively low GnPR values, and were of medium-high density and high site coverage, whereas the private mixed-use buildings in the study were largely more recently constructed buildings that have high GnPR values, with high site coverage and very high density.

An attempt was made to determine the correlation between GnPR level and buildings built before 1989, the year when GFA regulations were first launched. In fact, it took more time than expected for private real estate developers to respond to the regulations. Thus, a slight increase in GnPR level was observed much later around 2000. The land sub-use type was chosen as the only factor affecting a building's GnPR level instead of the 'land use building type', as some of the sub-land-uses (like factories and strata-landed housing) pulled down the GnPR values for the larger residential and industrial categories they fall under.

The mean GnPR for each of the ten sub-land-use categories, for the existing and the four simulated design scenarios, are presented in Table 1.6. For information and for the purpose of subsequent GnPR optimisations, Table 1.7 provides the summary of the various mean greenery costs of the 100 audited buildings for the existing and four simulated design scenarios per building, namely, the 'Enhanced 1', 'Enhanced 2', 'Maximum' and 'Ultimate' design scenarios by land use.

Table 1.8 shows another version of the summary for the various greenery cost means per sq. m. of the 100 audited buildings for the five design scenarios per building. On the whole, the mean maintenance, installation and total costs rose sharply between the 'Maximum' and 'Ultimate' design scenarios across all land use types. However, the mean maintenance, installation and total costs were found to either rise more gradually, stagnate or decline between the 'Enhanced 2' and the 'Maximum' design scenarios.

The highest mean total cost of about S$315 per sq. m. was observed for the 'Ultimate' design scenario for the sub-land-use 'Factory' category, with a high mean installation cost of about S$232 per sq. m. and the much lower mean maintenance cost of about S$83 per sq. m. The lowest mean total cost of about S$14 per sq. m. was observed for the 'Existing' design scenario of the sub-land-use 'Business park' category, which also had the third-lowest mean installation cost of about S$7 per sq. m. and the second lowest mean maintenance cost of about S$7 per sq. m. The sub-land-use 'Factory' category had the lowest mean installation cost of about S$3 per sq. m. for the 'Existing' scenario, but a relatively high mean maintenance cost of S$13 per sq. m. and a mean total cost of about S$16 per sq. m. The sub-land-use 'Mixed-residential' category has the

Table 1.6. Mean GnPRs and Standard Deviations (SDs) by land sub-use type for the five scenarios

Land sub-use	Scenario	Existing	Enhanced 1	Enhanced 2	Maximum	Ultimate
HDB flat	Mean	3.0923	3.8115	4.0077	4.2177	4.6346
	Std. deviation	1.61416	1.60818	1.56088	1.62125	1.53055
Condominium	Mean	2.6767	3.2200	3.4647	3.5980	4.0820
	Std. deviation	1.36903	1.44079	1.40175	1.42636	1.37851
Public-mixed	Mean	0.2325	0.3850	1.0925	1.5925	2.0425
	Std. deviation	0.10966	0.25723	0.35929	0.29579	0.60846
Private-mixed	Mean	2.2425	2.6538	2.9638	3.0625	3.3012
	Std. deviation	1.19791	1.22219	1.38578	1.38393	1.49180
Hotel	Mean	1.2233	1.7867	2.0033	2.2567	2.5500
	Std. deviation	0.77120	1.07202	0.96736	1.19580	1.30180
Office	Mean	1.0656	1.5633	2.1111	2.5356	3.3089
	Std. deviation	1.17932	1.42585	1.24561	1.18417	1.25508
Retail	Mean	0.9060	1.2933	1.5727	1.9113	2.3760
	Std. deviation	0.57765	0.70957	0.66893	1.19970	1.20250
Mixed-commercial	Mean	0.8450	1.0270	1.5910	1.7660	2.6280
	Std. deviation	1.00972	0.99490	0.99845	1.01488	1.40723
Business Park	Mean	2.3440	2.8000	3.2520	3.2920	3.7400
	Std. deviation	0.64493	0.76443	0.67559	0.64913	0.62598
Factory	Mean	0.5691	1.1536	1.6282	1.6955	2.0182
	Std. deviation	0.40488	0.74462	1.05432	1.06925	1.22446
Total	Mean	1.5930	2.0662	2.4338	2.6415	3.1306
	Std. deviation	1.38433	1.51744	1.44952	1.49055	1.52355

Source: Pomeroy & Broadway Malyan (2012); Author (2018)

Table 1.7. Greenery provision costs for the five design scenarios. (a) Installation cost; (b) Maintenance cost; (c) Total cost of greenery

Land sub-use\ Installation cost	**Existing**	**Enhanced 1**	**Enhanced 2**	**Maximum**	**Ultimate (with structural changes)**
HDB flat	$887,641	$1,302,276	$2,335,785	$4,603,695	$7,388,652
Condominium	$709,636	$1,473,408	$2,579,998	$4,164,848	$11,740,713
Public-mixed	$48,311	$72,760	$1,291,837	$4,527,544	$6,996,449
Private-mixed	$1,468,389	$1,754,234	$2,687,731	$3,660,955	$7,491,917
Hotel	$197,604	$348,622	$757,615	$2,146,947	$3,153,058
Office	$112,273	$217,693	$665,087	$1,950,180	$3,925,787
Retail	$394,066	$726,860	$1,360,066	$3,521,412	$5,170,964
Mixed-commercial	$80,774	$153,331	$735,828	$1,309,833	$4,096,703
Business Park	$584,648	$800,689	$2,274,989	$2,900,474	$6,196,491
Factory	$206,540	$649,151	$2,455,535	$3,123,403	$7,558,520
Total	$495,467	$832,763	$1,849,148	$3,302,702	$6,781,291
Land sub use\ Maintenance cost	**Existing**	**Optimum 1**	**Optimum 2**	**Maximum**	**Ultimate**
HDB flat	$227,916	$266,085	$455,146	$950,303	$1,467,103
Condominium	$913,562	$1,083,481	$1,282,376	$1,711,264	$2,264,867
Public-mix	$133,668	$180,134	$635,372	$1,397,640	$1,801,985
Private-mix	$442,756	$502,371	$660,417	$845,075	$1,158,877
Hotel	$447,879	$740,798	$799,689	$1,037,141	$1,159,887
Office	$376,095	$561,118	$640,026	$948,152	$944,567
Retail	$388,704	$518,536	$625,122	$1,192,145	$1,367,613
Mixed-commercial	$297,458	$584,986	$735,560	$866,860	$1,069,287
Business Park	$843,869	$989,513	$1,252,182	$1,368,438	$1,823,736
Factory	$398,882	$1,158,534	$1,496,107	$1,655,429	$2,194,344
Total	$457,103	$672,804	$872,596	$1,220,304	$1,589,119

Table 1.7. (*Continued*)

Land sub-use\ Total cost	**Existing**	**Enhanced 1**	**Enhanced 2**	**Maximum**	**Ultimate**
HDB	$1,115,557	$1,568,361	$2,790,931	$5,553,998	$8,855,755
Condo	$1,623,198	$2,556,889	$3,862,373	$5,876,111	$14,005,580
Public-mixed	$181,979	$252,894	$1,927,210	$5,925,184	$8,798,434
Private-mixed	$1,911,146	$2,256,605	$3,348,148	$4,506,030	$8,650,794
Hotel	$645,482	$1,089,420	$1,557,304	$3,184,088	$4,312,945
Office	$488,368	$778,811	$1,305,113	$2,898,332	$4,870,354
Retail	$782,769	$1,245,396	$1,985,188	$4,713,556	$6,538,577
Mixed-commercial	$378,232	$738,316	$1,471,389	$2,176,693	$5,165,990
Business Park	$1,428,517	$1,790,202	$3,527,170	$4,268,911	$8,020,227
Factory	$605,422	$1,807,686	$3,951,642	$4,778,832	$9,752,865
Total	$952,570	$1,505,567	$2,721,743	$4,523,006	$8,370,410

Source: Pomeroy & Broadway Malyan (2012); Author (2018)

Table 1.8. Total cost of greenery per sq. m. for the four design scenarios

Land sub-use	**Scenario**	**Existing**	**Enhanced 1**	**Enhanced 2**	**Maximum**	**Ultimate**
Maintenance Cost (S$ per sq. m., over ten years)						
Residential	Mean	**13.61**	**15.34**	**18.35**	**27.03**	**35.38**
	Std. deviation	27.87	28.58	30.71	34.98	36.63
Mixed-residential	Mean	**5.55**	**6.51**	**10.10**	**14.76**	**19.46**
	Std. deviation	6.08	6.90	9.72	10.50	15.47
Commercial (Hotel, office, retail, mixed)	Mean	**15.14**	**22.38**	**25.64**	**36.01**	**40.99**
	Std. deviation	18.12	25.75	26.44	33.29	36.39
Factory	Mean	**13.00**	**53.75**	**64.62**	**69.26**	**82.93**
	Std. deviation	11.42	67.33	82.74	82.75	105.09

(*Continued*)

Table 1.8. (*Continued*)

Land sub-use	**Scenario**	**Existing**	**Enhanced 1**	**Enhanced 2**	**Maximum**	**Ultimate**
Business Park	Mean	**7.15**	**9.30**	**13.97**	**15.02**	**20.86**
	Std. deviation	5.16	3.86	4.91	5.63	8.37
Installation Cost (S$ per sq. m.)						
Residential	Mean	**10.93**	**18.31**	**34.78**	**27.03**	**120.11**
	Std. deviation	9.49	12.56	26.05	34.98	108.82
Mixed-residential	Mean	**14.45**	**16.11**	**30.91**	**14.76**	**85.57**
	Std. deviation	18.30	18.51	29.64	10.50	33.49
Commercial (Hotel, Office, Retail, Mixed)	Mean	**5.37**	**13.27**	**31.89**	**36.01**	**124.08**
	Std. deviation	7.99	30.46	38.54	33.29	105.49
Factory	Mean	**2.87**	**18.49**	**76.65**	**69.26**	**232.23**
	Std. deviation	2.20	23.80	115.80	82.75	329.60
Business park	Mean	**6.63**	**9.12**	**34.37**	**15.02**	**78.72**
	Std. deviation	2.62	2.68	22.44	5.63	34.70
Total cost (S$ per sq. m.)						
Residential	Mean	**24.53**	**33.66**	**53.13**	**92.68**	**155.49**
	Std. deviation	35.60	38.30	53.67	82.11	128.09
Mixed-residential	Mean	**20.00**	**22.62**	**41.01**	**66.76**	**105.04**
	Std. deviation	23.78	24.54	38.52	43.42	46.82
Commercial (Hotel, Office, Retail, Mixed)	Mean	**20.51**	**35.65**	**57.52**	**107.27**	**165.07**
	Std. deviation	21.70	50.99	59.24	112.95	135.37

Table 1.8. (*Continued*)

Land sub-use	**Scenario**	**Existing**	**Enhanced 1**	**Enhanced 2**	**Maximum**	**Ultimate**
Factory	Mean	**15.87**	**72.24**	**141.26**	**166.42**	**315.16**
	Std. deviation	11.44	72.42	187.59	186.92	422.20
Business park	Mean	**13.78**	**18.42**	**48.34**	**55.02**	**99.58**
	Std. deviation	4.83	2.32	25.44	26.46	42.13

Source: Pomeroy & Broadway Malyan (2012); Author (2018)

lowest mean maintenance cost of about S$5.6 per sq. m. for the 'Existing' scenario, but with a mean installation cost of about S$14 per sq. m. and a mean total cost of about S$20 per sq. m.

Figure 1.5 depicts the hyperbolic slow-to-sharp rising trend of GnPR with the assigned total cost from the 'Existing' to the 'Ultimate' scenarios. Each land sub-use type's average level of increase in GnPR between their 'Existing' to 'Ultimate' design scenarios is as follows:

- Residential — by 1.5, with total cost increase of S$10 million;
- Mixed (Residential-commercial) — by 1.3, with total cost increase of S$7.4 million;
- Commercial — by 1.7, with total cost increase of S$4.9 million;
- Factory — by 1.5, with total cost increase of S$8.9 million;
- Business park — by 1.3, with total cost increase of S$6.6 million

Their average increase in GnPR level from the 'Maximum' to the 'Ultimate' design scenario is as follows:

- Residential — by 0.5, with total cost increase of S$5.9 million;
- Mixed (Residential-commercial) — by 0.3, with total cost increase of S$3.7 million;
- Commercial — by 0.6, with total cost increase of S$2.0 million;

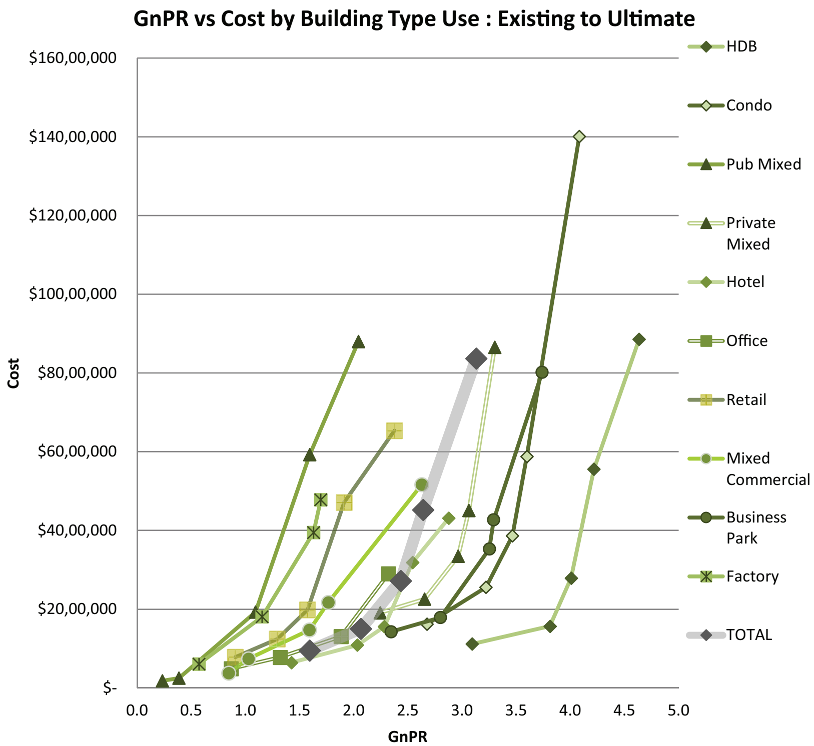

Fig. 1.5. GnPR vs. the total cost

Source: Author (2018)

- Factory — by 0.4, with total cost increase of S$4.8 million;
- Business park — by 0.4, with total cost increase of S$3.9 million.

A GnPR of 3.1 is thus observed to be achievable with a total cost of SS$8.4 million for the 'Ultimate' design scenario, while a GnPR of 2.6 with a total cost of S$4.6 million is achievable for the 'Maximum' design scenario.

The Marginal Cost Analysis (MCA) Model

The MCA model's empirical data was obtained from the building audit of 100 buildings. The associated Average Cost model, defined to be the total cost divided by GnPR level, is plotted in conjunction with the MCA model to generally validate the U-shape nature of the MCA model (observed in Fig. 1.5). The MCA model by the four land use categories was estimated and accordingly charted in a graph, together with its approximated polynomial function, to determine the narrow GnPR band around its minimum U-shaped point that reflects the optimal GnPR by land use. The narrow band is highlighted as the lowest marginal cost (MC) band as part of the figure's title of the respective MCA model concerned. The corresponding Average Cost curves represent a more smoothened version of the MCA model's curves and they broadly affirm the same pattern of the MC curves.

The MCA model itself was estimated using the building audit data. The lowest MC was found to be at the following GnPR levels for five land uses:

Land use, GnPR levels and the total cost

- Residential land use: the existing condition's GnPR is 3.41 while the combined option's is 3.67 with a total cost of S$1,536,819.
- Mixed (residential-commercial) land use: the existing condition's GnPR is 1.03 while the combined option's is 2.71 with a total cost of S$5,125,360.
- Commercial land use: the existing condition's GnPR is 0.56 while the combined option's is 2.13 with a total cost of S$425,440.
- Industrial land use (business parks): the existing condition's GnPR is 1.73 while the combined option's is 1.97 with a total cost of S$265,992.
- Industrial land use (factories): the existing condition's GnPR is 0.25 while the combined option's is 1.66 with a total cost of S$14,274,033.

Optimal GnPR values for various building types in Singapore

The optimised GnPR in Tables 1.9, 1.10 and 1.11 adopt the heuristic algorithm that conforms to the usual practice of imposing constraints on a maximising objective function. The design and economic optimisation approaches are shown below. Such an increasing function for GnPR is

Table 1.9. Heuristic optimisation model, Part 1: Design optimisation
(Part 1: Heuristically modelled optimal gnpr by land use: Design optimisation)

Land Use	Building Type	Mean GnPR					GnPR distribution (<2SD = 95%confidence)										Optimal GnPR	
		Existing	Enhanced 1	Enhanced 2	Maximum	Ultimate	Mean	SD	mean+ 0.25SD	mean+ 0.5SD	mean+ 0.75SD	mean+ 1SD	mean+ 1.25SD	mean+ 1.5SD	mean+ 1.75SD	mean+ 2SD	low	high
Residential	Public	3.09	3.81	4.01	4.22	4.63	3.09	1.61	3.50	3.90	4.30	4.71	5.11	5.51	5.92	6.32	3.1	4.3
	Private	2.68	3.22	3.46	3.60	4.08	2.68	1.37	3.02	3.36	3.70	4.05	4.39	4.73	5.07	5.41	2.7	4.1
	Strata landed Housing	0.98	1.50	2.15	2.15	2.97	0.98	0.34	1.06	1.15	1.23	1.32	1.40	1.49	1.57	1.66	1.0	1.7
Mixed Residential-Commercial	Public	0.23	0.39	1.09	1.59	2.04	0.23	0.11	0.26	0.29	0.31	0.34	0.37	0.40	0.42	0.45	0.2	0.5
	Private	2.24	2.65	2.96	3.06	3.30	2.24	1.20	2.54	2.84	3.14	3.44	3.74	4.04	4.34	4.64	2.2	3.1
Commercial	Hotel	1.22	1.79	2.00	2.26	2.55	1.22	0.77	1.42	1.61	1.80	1.99	2.19	2.38	2.57	2.77	1.2	2.4
	Office	1.07	1.56	2.11	2.54	3.31	1.07	1.18	1.36	1.66	1.95	2.24	2.54	2.83	3.13	3.42	1.1	3.1
	Retail	0.91	1.29	1.57	1.91	2.38	0.91	0.58	1.05	1.19	1.34	1.48	1.63	1.77	1.92	2.06	0.9	2.1
	Mixed	0.85	1.03	1.59	1.77	2.63	0.85	1.01	1.10	1.35	1.60	1.85	2.11	2.36	2.61	2.86	0.8	2.6
Industrial	Business park	2.34	2.80	3.25	3.29	3.74	2.34	0.64	2.51	2.67	2.83	2.99	3.15	3.31	3.47	3.63	2.3	3.6
	Factory and warehouse	0.57	1.15	1.63	1.70	2.02	0.57	0.40	0.67	0.77	0.87	0.97	1.08	1.18	1.28	1.38	0.6	1.4
Public space		0.59	0.93	1.12	1.19	1.59	0.59	0.13	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.6	0.9

Source: Author (2016)

Table 1.10. Heuristic optimisation model, Part 2: Marginal Cost (MC)
(Part 2: Heuristically modelled optimal GnPR by land use: Economic optimisation)

Land use	Building type	Existing design scenario		Ultimate design scenario		Marginal cost optimisation		Optimal GnPR (design)		Optimal GnPR (design and economic)		Comments
		GnPR	TC	GnPR	TC	GnPR	MC	low	high	low	high	
Residential	Public	3.092	1,115,557	4.635	8,855,755	4.70	2,376,191	3.1	4.3	3.1	4.7	The high GnPR is changed
	Private	2.677	1,623,198	4.082	14,005,580	2.30	325,771	2.7	4.1	2.7	4.1	
	St Landed	0.98	652,391	2.965	8,306,573			1.0	1.7	1.0	1.7	
Mixed Residential-Commercial	Public	0.233	181,979	2.043	8,798,434	1.30	7,612,063	0.2	0.5	0.2	0.5	No. of samples is too small
	Private	2.243	1,911,146	3.301	8,650,794	4.2	4,789,357	2.2	3.1	2.2	4.2	The high GnPR is changed
Commercial	Hotel	1.223	645,482	2.55	4,312,945	1.30	1,666,747	1.2	2.4	1.2	2.4	
	Office	1.066	488,368	3.309	4,870,354	0.90	364,344	1.1	3.1	1.1	3.1	
	Retail	0.906	782,769	2.376	6,538,577	2.50	1,137,304	0.9	2.6	0.9	2.6	
	Mixed	0.845	378,232	2.628	5,165,990	1.60	624,423	0.8	2.6	0.8	2.6	
Industrial	Business park	2.344	1,428,517	3.74	8,020,227	1.97	265,992	2.3	3.6	2.3	3.7	No. of samples is too small
	Factory and warehouse	0.569	605,422	2.018	9,752,865	1.23	453,529	0.6	1.4	0.6	1.4	
Public space		0.585	666,752	1.585	12,272,284			0.6	0.9	0.6	0.9	

Source: Author (2016)

Table 1.11. Optimal GnPR

		Optimal GnPR (design and economic)	
Land use	**Building type**	**Low**	**High**
Residential	Public	3.1	4.7
	Private	2.7	4.1
Mixed residential-commercial	Public	0.2	0.5
	Private	2.2	4.2
Commercial	Hotel	1.2	2.4
	Office	1.1	3.1
	Retail	0.9	2.6
	Mixed	0.8	2.6
Industrial	Business park	2.3	3.7
	Factory and warehouse	0.6	1.4

Source: Pomeroy & Broadway Malyan (2012); Author (2018)

represented by increasing the standard deviation (SD) from the mean GnPR within the boundary range of between +0.25SD and +2.0SD. In practice, for a normally distributed GnPR, approximately 95 per cent of the data points would fall within the spread of ±1.96SD, i.e. ±2.0SD from its mean. Such a 95 per cent confidence interval would represent the extreme +2SD boundary condition for GnPR, at which the optimal value can be realistically achieved. The step wise rules of the GnPR heuristic optimisation model are outlined below. The lowest and closest GnPR value for an incremental SD to the Ultimate GnPR is chosen as that particular highest boundary for the optimal GnPR level. On practical grounds, the optimum GnPR is appropriately presented as a range between the high and low optimum GnPR, making sure the high optimum GnPR does not exceed the Ultimate GnPR value.

Part 1: Design optimisation (see Table 1.9)

1. The mean GnPR for the 'Existing' design scenario is the low boundary of the Optimal GnPR.

2. The mean GnPR for the 'Ultimate' design scenario is compared with the GnPR values within the +0.25SD and +2.0SD boundary range.
3. The lowest and closest GnPR value for an incrementing SD to the mean GnPR for the 'Ultimate' design scenario is chosen as that particular highest boundary for the Optimal GnPR level.
4. The 2SD rule should hit at least the GnPR of the 'Enhanced 1' design scenario.

Part 2: Economic optimisation (see Table 1.10)

1. The total cost (TC) for the 'Existing' and 'Ultimate' design scenarios are provided for information. The TC comprises the green landscaping investment cost and the ten-year maintenance cost for the low and high GnPR values, for private real estate developer-investors.
2. The presented cost figures are the associated design cost of greenery (i.e. the cost that is nearest to the modelled optimum GnPR values).
3. The optimal marginal GnPR values are compared with the optimal design GnPR values: The optimal value derived by the economic approach should be within the optimal GnPR range derived by the design approach. This indicates that the optimal GnPR (for the design and economic optimisations) is conditioned by the returns to scale that are expected of greenery investing.

The results of the heuristically modelled Optimal GnPR for ten building types are summarised in Table 1.11.

Concluding Remarks

So far, two objectives, namely, to provide the optimal levels of the green plot ratio (GnPR) for the various land-use types; and to establish the capital and maintenance costs for various levels of greenery provision have been achieved. We next progress onwards to completing the potential landscape guidelines for the application of the optimal GnPR levels, to facilitate a sustainable land scape for Singapore.

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